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DEVELOPMENT OF A MANOUEVRING MODEL FOR THE RAN PRECURSOR MINE SWEEPING

(2)

BRENDON ANDERSON AND GARY CAMPANELLA

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Development of a Manoeuvring Model for the RAN Precursor Mine Sweeping Drone Boat

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Abstract

A three-degree-of-freedom mathematical model has been developed to describe the zigzag manoeuvring behaviour of a prototype hull form used in the Royal Australian Navy precursor mine sweeping drone boat. The model predicts the yaw rate of the vessel in response to the angle of thrust that a single outboard motor makes with respect to the centre line of the boat. The outboard motor is assumed to supply a constant thrust. This report describes the development of the model from first principles and its transformation into a form suitable for use in closed loop control modelling. The coefficients of the model were determined using full scale manoeuvring data for the prototype hull form.

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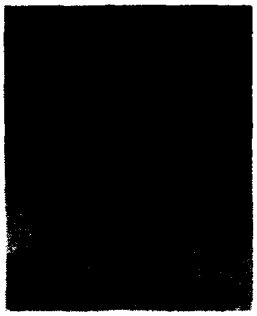

Brendon Anderson graduated with a BSc, majoring in Applied Mathematics, from Monash University in 1989. In 1990 he joined the Materials Research Laboratory where he has been involved in the study of manoeuvring performance of remotely operated vehicles with relevance to areas of maritime defence. Mr Anderson is currently undertaking a Master's of Engineering Science with the University of Tasmania in conjunction with the Australian Maritime Engineering Cooperative Research Centre, and the Materials Research Laboratory, in the prediction of hydrodynamic characteristics of underwater bodies and the analysis of data arising from planar motion mechanism testing.

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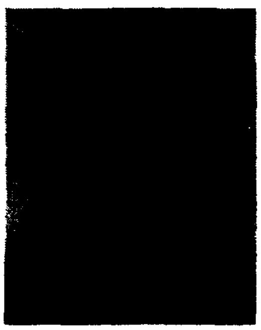

Gary Campanella graduated BSc, majoring in Physics, and BComm Eng from Latrobe University in 1979 and 1981 respectively. He joined the Materials Research Laboratory in 1982 where he was involved in developing high speed instrumentation and techniques for the study of shock and related phenomena. Since 1989 he has been leading the development of capability to measure and predict the operational performance of unmanned marine vehicles in mine countermeasure applications. Mr Campanella is currently undertaking a Master's of Engineering in Systems Engineering with the Royal Melbourne Institute of Technology.

Contents

Development of a Manoeuvring Model for the RAN Precursor Mine Sweeping Drone Boat

1. *Introduction*

The Precursor Mine Sweeping Drone Boat under development by the Royal Australian Navy will be based on a commercially available tri-hulled vessel made of fibreglass. The vessel will be eight metres in length and powered by two 1000 kW outboard motors. The boat will be fitted with a radio position fixing system and will tow an acoustic influence mine sweeping device.

The mine sweeping drone boat will be operated remotely via a radio link to a shore station. The boat will be equipped with a programmable autopilot to maintain the vessel close to a defined track. The drone boat concept is depicted in figure (1).

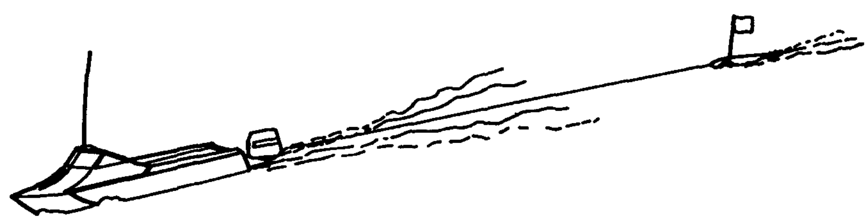

Figure 1: ***The drone boat towing a mine sweeping device. (The sweeping device is submerged, the semi-submerged towfish indicates its position.)***

The work described in this report was conducted at a time prior to the construction of the drone boat hull. However, the RAN supplied a six metre version of the same hull form which was used for preliminary investigations of the concept. This report describes the development of a horizontal plane, three-

degree-of-freedom mathematical manoeuvring model for this prototype of the drone boat hull. The model predicts the yaw rate of the vessel as a function of the angle of thrust. The outboard motor is assumed to supply a constant thrust. The effects of wind and sea-state are not considered. The manoeuvring model was specifically developed to simulate and compare the performance of two commercially available autopilot systems (Campanella, Anderson and Spirovski).

The specification for the drone boat autopilot system is shown in figure 2. The drone boat autopilot is programmed with baseline coordinates defined by points A and B. The distance the boat wanders from this baseline is called the cross-track error (Y_{te}). This must not be greater than ten metres on either side of the baseline. The autopilot control law is based on measurements of the instantaneous heading of the boat (ψ) with respect to the track, the known required track heading or reference heading, and the cross-track error (Y_{te}).

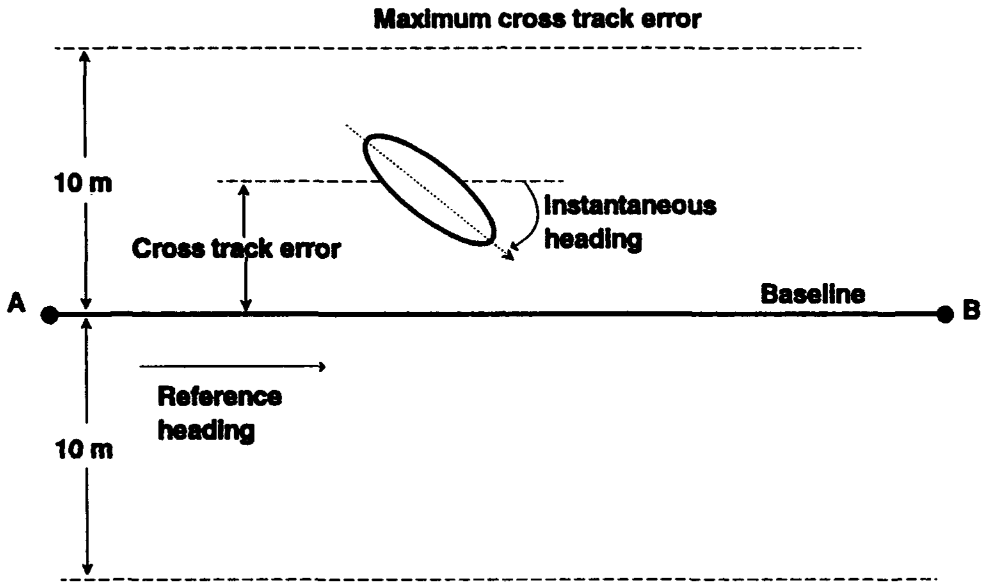

Figure 2: Guidance and control specification for the drone boat autopilot system.

2. *Derivation of the Manoeuvring Model*

The manoeuvring model is required to predict the vessel rate of change of direction (yaw rate, r) in response to the change in angle of the outboard motor with respect to the centreline of the boat (rudder angle, δ). The outboard motor is assumed to produce constant thrust. The model is developed for calm water and neglects forces on the boat due to wind and current. The tow device has been assumed to be a rigid part of the drone boat. The extra drag force due to the tow is accounted for in the model coefficients.

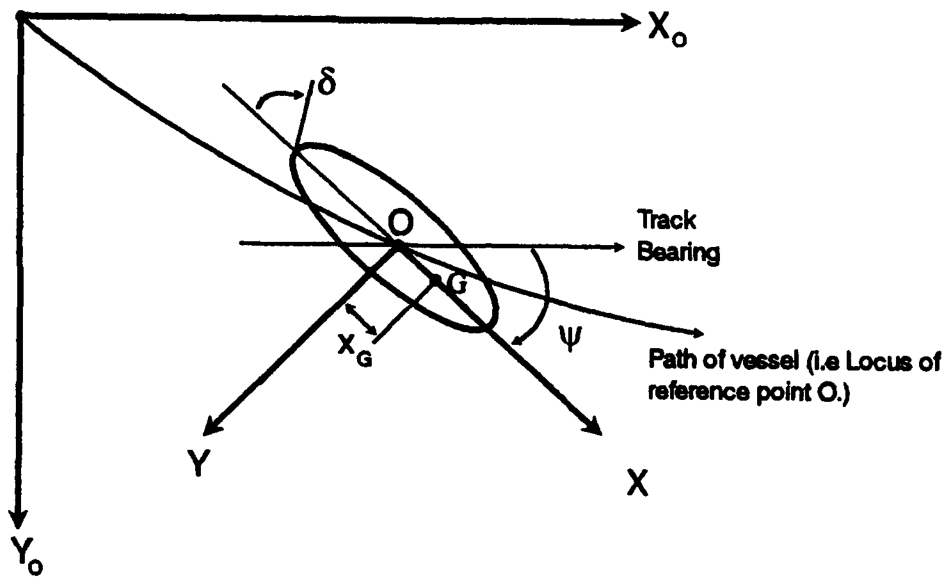

Figure 3: A body fixed coordinate system for surface vessels.

Figure 3 shows the coordinate system used in the equations of motion for the drone boat, where x_o and y_o are the global coordinate axes fixed in space and where x_o lies in the same direction as the baseline AB. The forward direction of the boat lies along the x-axis while the y-axis denotes sidewards direction. The x and y axes are centred at a fixed arbitrary point O on the boat to form the local or body fixed coordinate system. This coordinate system follows the conventional right hand rule, giving all rotations a positive sense in the clockwise direction. The angle ψ represents the angle of rotation of the boat's x-axis with respect to the global x_o-axis.

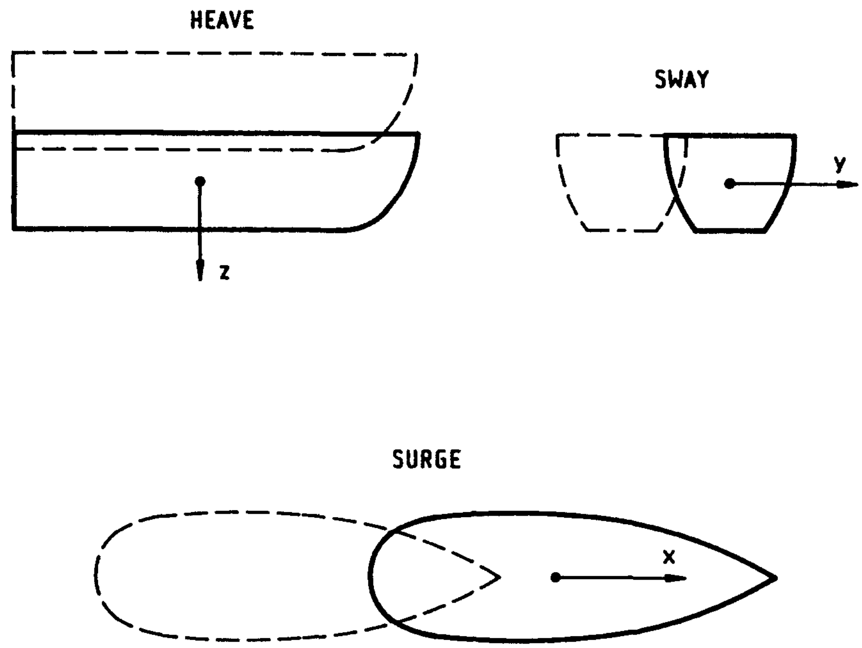

Figure 4: Displacement motions of a surface vessel.

Figure 4 illustrates the three displacement motions; heave, sway and surge. The motion of the boat in the z axial direction is designated heave and is positive downwards. Sidewards motion of the boat is sway. Surge is the third linear motion and is due to forward displacement in the x-axial direction. Heave is neglected in the horizontal manoeuvring model.

Figure 5 illustrates the three rotational motions; pitch, roll, and yaw.

Roll is the rotation about the x-axis, while rotation about the y-axis is pitch. Yaw is the rotation about the z-axis of the vessel. Pitch and roll are neglected in the following horizontal plane model. In theory, any of the six motions can occur in the absence of the other, but in practice coupled motions will exist.

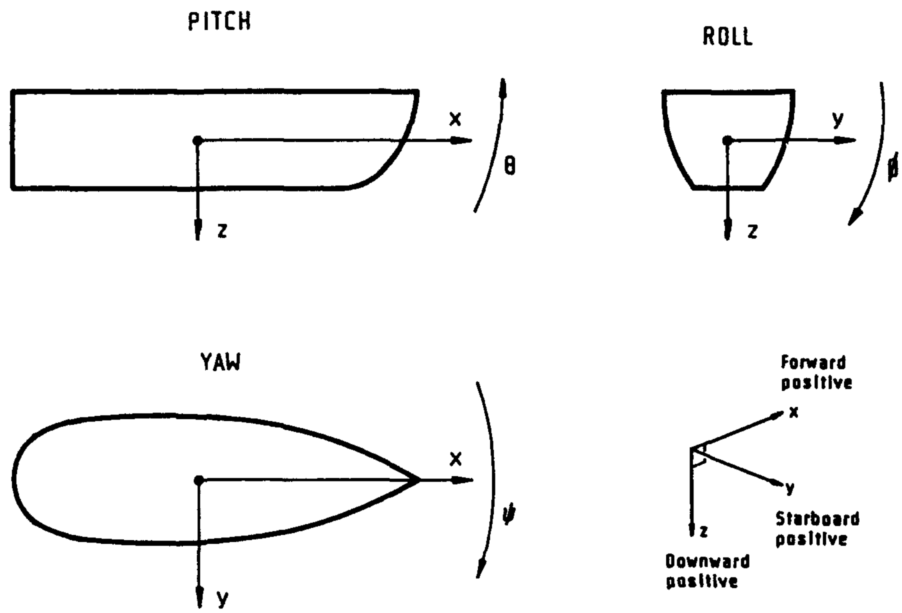

Figure 5: Rotational motions of a surface vessel.

2.1 *Mathematical Development*

The following is a derivation of the manoeuvring equations for the mathematical model, based on the work of Abkowitz (1969), Gill (1979) and Clarke (1982). The essential assumptions of the model are summarised as follows:

1. The variation in the mass of the drone boat due to the consumption of fuel is negligible.
2. Forces on the boat due to the rotation of the Earth are neglected. This is equivalent to neglecting Coriolis accelerations.
3. The model is linear.
4. Pitch, roll, and heave are neglected.
5. Speed loss in the surge direction is negligible.
6. The thrust produced by the propellor is constant and moments due to the rotation of the propellor are neglected.
7. The boat is symmetrical about the x-axis.
8. The boat/tow system is assumed rigid in the model.
9. The oscillatory nature of the manoeuvres is assumed to have negligible effect on the external forces applied to the boat/tow system.

Consider the vessel in figure (3) proceeding along some arbitrary path with linear and rotational velocity U_G and Ω_G respectively. The application of Newton's second law of motion expressed in the global coordinate system yields the following equations:

$$F = \frac{d}{dt}(mU_G) \qquad \text{... (1)}$$

$$M_G = \frac{d}{dt}(I_G\Omega_G) \qquad \text{... (2)}$$

Where F = The resultant externally applied force vector acting on the boat at the centre of gravity (considered as a column vector).

M_G = The resultant externally applied moment vector acting on the boat about the centre of gravity (considered as a column vector).

U_G = The linear velocity vector with respect to the centre of gravity (considered as a column vector).

Ω_G = The rotational velocity vector of the boat about the centre of gravity (considered as a column vector).

m = The dry mass of the body.

I_G = A 3x3 matrix of the body's moment of inertia about an orthogonal axes parallel to x,y,z through the centre of gravity.

Although the expressions are more complicated, modelling the forces about the local origin O is desirable since O can be placed at a point on the body where symmetry might be considered to exist. Figure (6) shows the vector relationship between the two coordinate systems, one located at the centre of gravity, and the other at an origin O.

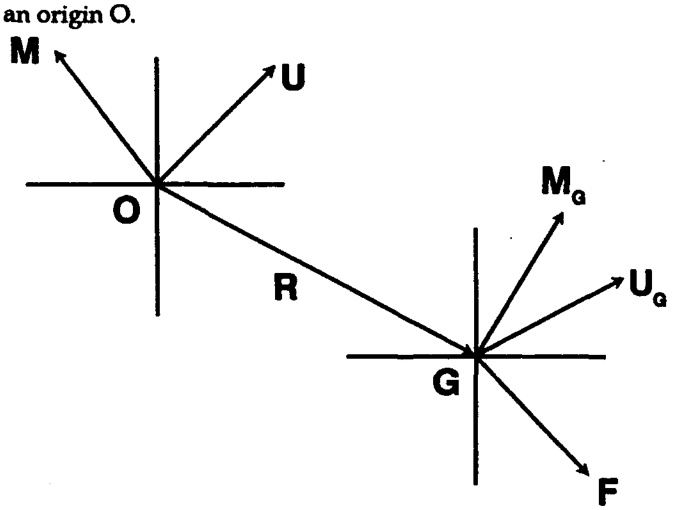

Figure 6: Two body fixed coordinate systems showing the body's motion vectors.

Since the velocity at the centre of gravity U_G is equal to the velocity U at the origin O, plus the velocity of the centre of gravity relative to O i.e. $U_G = U + \Omega \times R$, then equation (1) can be expressed as shown in equation (3).

$$\mathbf{F} = m\frac{d}{dt}(\mathbf{U} + \mathbf{\Omega} \times \mathbf{R}) \qquad \text{... (3)}$$

Where	**R**	=	The position vector of the boat centre of gravity with respect to the origin O.
	Ω	=	The rotational velocity vector of the boat about the origin O.
	U	=	The linear velocity of the boat at the origin O.
	×	=	The vector cross product operator.

The moment about the origin O is equal to the moment about the centre of gravity plus the moment due to the force **F** acting over the distance **R**. The moment is therefore given by

$$\mathbf{M} = \mathbf{M}_G + \mathbf{R} \times \mathbf{F}$$

Substituting for $\mathbf{M}_G$ and **F**, where

$$\mathbf{M}_G = \frac{d}{dt}(\mathbf{I\Omega}) - m\left(\mathbf{R} \times \frac{d^2\mathbf{R}}{dt^2}\right)$$

and **F** is given by equation (3) the following expression for the moment about the origin results.

$$\mathbf{M} = \frac{d}{dt}(\mathbf{I\Omega}) + m\,\mathbf{R} \times \frac{d}{dt}\,(\mathbf{U}) \qquad \text{... (4)}$$

where $\mathbf{I}$ is a 3x3 matrix of the moment of inertia about the origin O,

$$\text{such that } \mathbf{I} = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{yx} & I_{yy} & -I_{yz} \\ -I_{zx} & -I_{zy} & I_{zz} \end{bmatrix} \text{ and}$$

M is the moment acting on the boat about the centre of gravity (considered as a column vector).

Since pitch, heave and roll are neglected, the vectors arising in the model are:

$$\mathbf{F} = (X,\ Y,\ 0)^T$$
$$\mathbf{M} = (0,\ 0,\ N)^T$$
$$\mathbf{\Omega} = (0,\ 0,\ r)^T$$
$$\mathbf{U} = (u,\ v,\ 0)^T$$
$$\mathbf{R} = (x_G,\ 0,\ 0)^T$$

Where u = The component of the boat's velocity resolved along the x-axis.
v = The component of the boat's velocity resolved along the y-axis.
r = The component of angular velocity of the boat resolved about the z-axis.
x_G = The position of the boat's centre of gravity along the x-axis with respect to O.

Expanding equations (3) and (4) into their components, and using the values given for **F, M, Ω, U** and **R** above, results in the following expressions:

$$m(\dot{u} - rv - x_G r^2) = X \qquad \text{... (5)}$$

$$m(\dot{v} + ru + x_G \dot{r}) = Y \qquad \text{... (6)}$$

$$I_{zz}\dot{r} + m x_G(\dot{v} + ru) = N \qquad \text{... (7)}$$

Now consider the vessel to have velocities and accelerations given by $u_o, v_o, r_o, \dot{u}_o, \dot{v}_o, \dot{r}_o$. If each term is perturbed by a small amount then the resultant velocities and accelerations are given by:

$$u = \Delta u + u_o$$

$$v = \Delta v + v_o$$

$$r = \Delta r + r_o$$

$$\dot{u} = \Delta\dot{u} + \dot{u}_o$$

$$\dot{v} = \Delta\dot{v} + \dot{v}_o$$

$$\dot{r} = \Delta\dot{r} + \dot{r}_o$$

$$Y = Y_o + \Delta Y$$

Consider now the development of the sway force model. Expanding the sway force equation (6) in terms of the above variables gives:

$$m[(\Delta\dot{v} + \dot{v}_o) + (\Delta r + r_o)(\Delta u + u_o) + x_G(\Delta\dot{r} + \dot{r}_o)] = Y_o + \Delta Y \qquad \text{..(8)}$$

Equation (8) is simplified by considering the case of steady state motion where the vessel is travelling with constant forward speed, with small disturbances occurring about this motion. Hence

$$v_o = \dot{v}_o = r_o = \dot{r}_o = \dot{u}_o = Y_o = 0, \text{ and } u_o \neq 0.$$

Therefore $v = \Delta v, r = \Delta r, \dot{u} = \Delta\dot{u}, \dot{v} = \Delta\dot{v}, \dot{r} = \Delta\dot{r}, Y = \Delta Y$ and $u = \Delta u + u_o$.

Neglecting the non-linear terms, the expression for the sway force is given by;

$$m(\dot{v}+r u_o+x_G \dot{r})=Y \qquad \text{... (9)}$$

Similarly, the yaw moment equation is given by

$$I_{zz}\dot{r}+mx_G(\dot{v}+ru_o)=N \qquad \text{... (10)}$$

and the surge equation is given by

$$m(\dot{u})=X \qquad \text{...(11)}$$

Assuming that Δu is small, then $\dot{u}$ is negligible, therefore equation (11) is neglected here. Hence equations (9) and (10) form the basis of the mathematical model.

X and Y denote the sum of resolved components of external forces in the surge and sway directions respectively, and N gives the sum of external moments about the z-axis. In the case of the net external sway force:

$$\begin{aligned} Y &= \sum Y_i \\ &= Y_T + Y_H + Y_E \end{aligned}$$

Where Y_T are the thrust forces in the sway direction,
Y_H are the hydrodynamic forces in the sway direction, and
Y_E are any other external forces which act on the body.

Assuming that $Y_E = 0$, the hydrodynamic and thrust forces which act on the drone boat in the sway direction are assumed to be a function of the variables $v,\dot{v},r,\dot{r},\delta$, such that:

$$\begin{aligned} Y &= Y_H + Y_T \\ &= Y\left(v,\dot{v},r,\dot{r},\delta\right) \end{aligned} \qquad \text{... (12)}$$

Where δ is the angle of the control surface (or in the case of the drone boat, the outboard motor) with respect to the centreline of the body. δ is the resultant of a steady value δ_o and a small increment $\Delta\delta$.

A first order Taylor series expansion of the sway force is formed about the equilibrium values of the dynamic variables and neglecting terms higher than the first order, giving

$$Y=Y_o+\frac{\partial Y}{\partial v}\bigg|_{v=v_o}\Delta v+\frac{\partial Y}{\partial \dot{v}}\bigg|_{\dot{v}=\dot{v}_o}\Delta \dot{v}+\frac{\partial Y}{\partial r}\bigg|_{r=r_o}\Delta r+\frac{\partial Y}{\partial \dot{r}}\bigg|_{\dot{r}=\dot{r}_o}\Delta \dot{r}+\frac{\partial Y}{\partial \delta}\bigg|_{\delta=\delta_o}\Delta\delta \qquad \text{... (13)}$$

The literature expresses the partial derivatives as follows:

$$Y_v = \frac{\partial Y}{\partial v}\bigg|_{v=v_o}, \text{ etc.}$$

This is not to be confused with the variables Y_T and Y_H which use uppercase letters for the subscripts to denote a particular component of the sway force. Using this notation and recognising that the steady state sway force $Y_o = 0$, and the steady state outboard motor angle $\delta_o = 0$, equation (13) becomes

$$Y = Y_v v + Y_{\dot{v}} \dot{v} + Y_r r + Y_{\dot{r}} \dot{r} + Y_\delta \delta \qquad \text{... (14)}$$

The term $Y_\delta \delta$ models the sway force of the outboard motor's thrust. This is a very simple model which assumes that the motor produces constant thrust and that δ is small.

The partial derivatives, otherwise known as hydrodynamic coefficients or derivatives, are a function of frequency. Therefore, the correct representation for Y_v is $Y_v(\omega)$ where ω is the angular frequency associated with the oscillation of the boat's motion. The frequency of the manoeuvres for the drone boat is expected to be small and so the coefficients can be taken as constants. Substituting equation (14) into (9) and rearranging, gives:

$$(Y_{\dot{v}} - m)\dot{v} + Y_v v + (Y_{\dot{r}} - m x_G)\dot{r} + (Y_r - m u_o) r + Y_\delta \delta = 0 \qquad \text{... (15)}$$

The same procedure applied to the yaw moment equation (10) gives:

$$(N_{\dot{v}} - m x_G)\dot{v} + N_v v + (N_{\dot{r}} - I_{zz})\dot{r} + (N_r - m x_G u_o) r + N_\delta \delta = 0 \quad \text{... (16)}$$

The manoeuvring model, defined by equations (15) and (16) was used as the open loop transfer function to be controlled by the drone boat autopilot control law. For ease of computer simulation the open loop manoeuvring model and closed loop control model were transformed to the z-domain. An s-domain representation is required as an intermediate step (Campanella, Anderson, and Spirovski).

The differential operator d/dt is replaced with the Laplacian s, in equations (15) and (16), and rearranged to give the following equation:

$$\frac{\bar{r}}{\bar{\delta}} = \frac{(Es+F)I - (As+B)J}{(As+B)(Cs+D) - (Es+F)(Gs+H)} \qquad \text{.. (17)}$$

where $\bar{r} = \bar{r}(s)$ [the Laplace transform of $r(t)$]

$\bar{\delta} = \bar{\delta}(s)$ [the Laplace transform of $\delta(t)$]

$A = Y_{\dot{v}} - m$

$B = Y_v$

$C = N_{\dot{r}} - I_{zz}$

$D = N_r - m x_G u_o$

$E = N_{\dot{v}} - m x_G$

$F = N_v$

$G = Y_{\dot{r}} - m x_G$

$H = Y_r - m u_o$

$I = Y_\delta$

$J = N_\delta$

Equation (17) can be simplified further to give:

$$\frac{\bar{r}}{\bar{\delta}} = \frac{K(s+a)}{s^2+bs+c} \qquad \text{... (18)}$$

Where $\bar{\delta}$ and $\bar{r}$ are the outboard angle and the yaw rate in the s-plane respectively. K, a, b, and c are functions of the hydrodynamic coefficients. This equation represents the open loop transfer function given in the s-domain of the change in boat heading in response to change in angle of thrust of the outboard motor.

3. *Determining the Model Coefficients*

The model parameters K, a, b, and c were determined by fitting system response measurements to the model form described in equation (18). The process of developing the mathematical manoeuvring model of a particular vehicle is summarised in figure (7).

The formulation of the model can be approached in either of two ways; firstly using a physical approach which builds a model based on known properties and an understanding of the underlying physical processes of the system, or secondly using a non-physical approach where the physical properties or mechanisms of the system may not be completely known, or are too complex to be modelled, or both.

The approach used in this report was a combination of both in that the form of the model was derived from force and moment equations expressed with hydrodynamic coefficients in a body-fixed coordinate system. For ease of computer simulation the expressions were transformed to a transfer function in the s-domain where the coefficients do not relate simply to the standard hydrodynamic derivatives.

There are several approaches to the evaluation of hydrodynamic coefficients. One such approach is the tank testing of scale models. Scale model testing involves subjecting a scale model of the hull form to precisely controlled motions in a fluid flow. Forces acting on the scale model are measured and from this hydrodynamic coefficients are derived. This method involves the use of

specialised facilities such as towing tanks, circulating water channels, and planar motion mechanisms (Gill 1979).

The approach used here was to derive the required modelling parameters from full-scale manoeuvres. In its most basic form, this involves conducting manoeuvres with the actual vessel, in still waters, while measuring control surface angles (the stimulus), and the boat heading (the response). Recursive algorithms or trial and error methods can be employed to fit the experimental data to the postulated model form and so derive the model parameters.

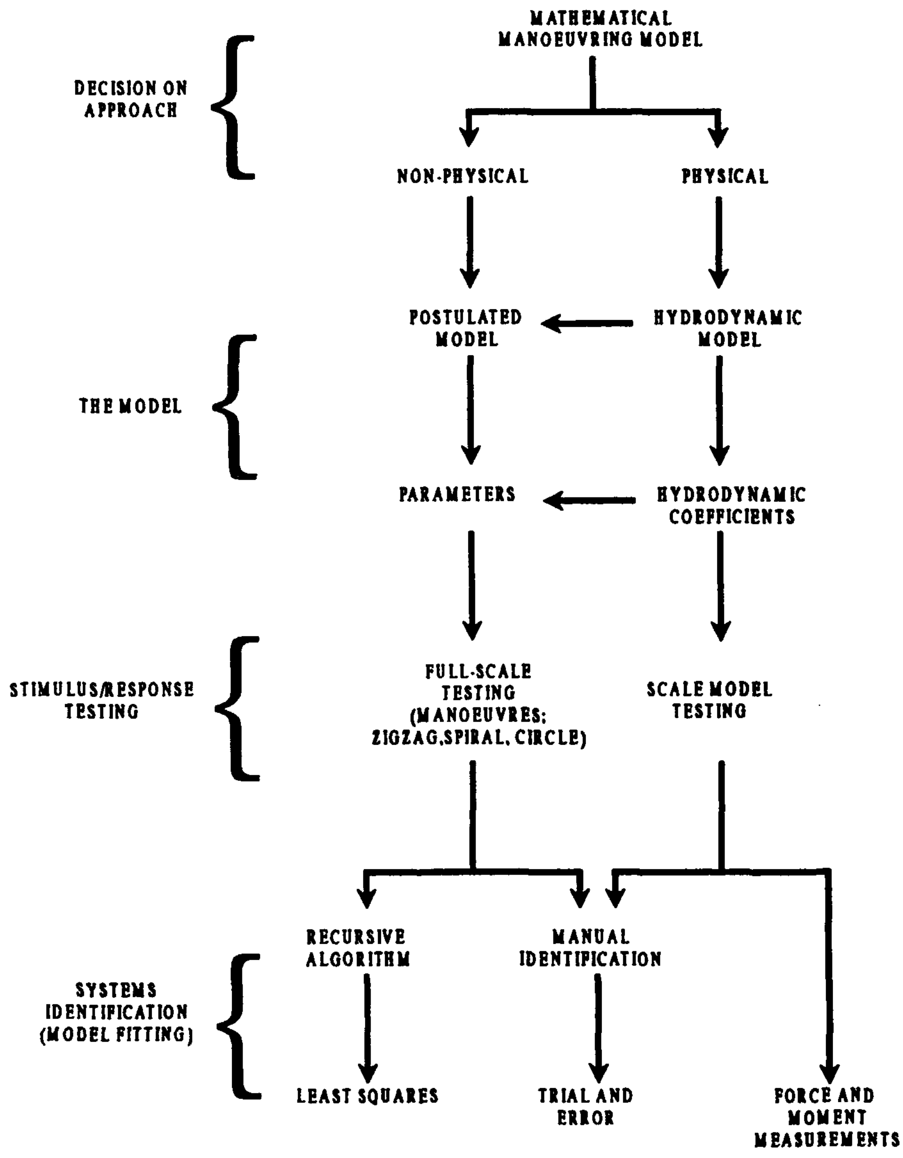

Figure 7: The system identification process.

4. *Full-Scale Drone Boat Manoeuvring Experiment*

A manoeuvring trial of the prototype drone boat was conducted at HMAS *Creswell*, Jervis Bay, Australian Capital Territory. Set manoeuvres were performed and measurements of rudder angle, boat heading, and speed in the surge direction were taken. Manoeuvres were conducted with and without the towed acoustic mine sweeping device. All manoeuvres were performed in zero sea-state by a helmsman.

Renilson (1988) and Abkowitz (1969) describe several types of manoeuvres suitable for characterising the full scale manoeuvring performance of vessels. The "zigzag" manoeuvre was used in this experiment. As a transient manoeuvre it allows both the acceleration and velocity components to be derived. Abkowitz (1980) considers a 10° zigzag to be a mild manoeuvre, where the significant contribution to the forces is made by linear terms, which is appropriate for the drone boat manoeuvring model.

In order to perform the zigzag, the boat was set on a straight course at a constant initial velocity of 7 knots. For a 10° manoeuvre, the helmsman set the rudder 10° to starboard. When the boat heading changed by 10°, the rudder was then set 10° to port. By continuing this action the vessel was made to zigzag.

Manoeuvring data were recorded for both a 10° and a 5° zigzag. The acoustic mine sweeping device was attached for a 10° manoeuvre.

The boat was fitted with a Coursemaster Model CM500 Series 2 marine autopilot system which was primarily used as the means of digitising and scaling the boat heading sensor signal. The rudder angle and boat heading sensors were manufactured and fitted by Coursemaster for the support of their autopilot system. Boat speed was measured with a conventional impellor-speed-log. Rudder angle was measured with a potentiometer-based transducer. A fluxgate compass was used for measuring the boat heading.

The digitised boat heading data were transferred to an MRL-developed data recorder. The drone boat was fitted with a HamilHaven Type 8904 data logger and this was used to acquire velocity and rudder angle data. Data were transferred to the MRL data logger after each manoeuvre.

The MRL data recorder was a Toshiba T1600/40 IBM compatible "laptop" personal computer. Data acquisition software was developed in Turbo Pascal which read data from the computer serial port and wrote them to a disk file.

5. *Results*

A graphical computer simulation of the manoeuvring model was developed in DOS Turbo Pascal and implemented on an IBM compatible personal computer. The input to the program requires, rudder angle as a function of time, the boat's initial forward speed, and a set of values for the coefficients described in equation (18). The program predicts the boat's response to the input data and plots boat heading as a function of time. The values of the coefficients shown below were derived by trial and error. The comparison between the simulation and the trial data allowed the coefficients to be adjusted until the best fit, as judged by eye were obtained. Initial values for the coefficients were generated from estimates of

hydrodynamic derivatives for the drone boat hull form supplied by Renilson(1990).

Figures (8) and (9) show simulated and actual boat heading for two different manoeuvres of the drone boat without a tow. Both manoeuvres were performed with an initial forward speed of 7 knots.

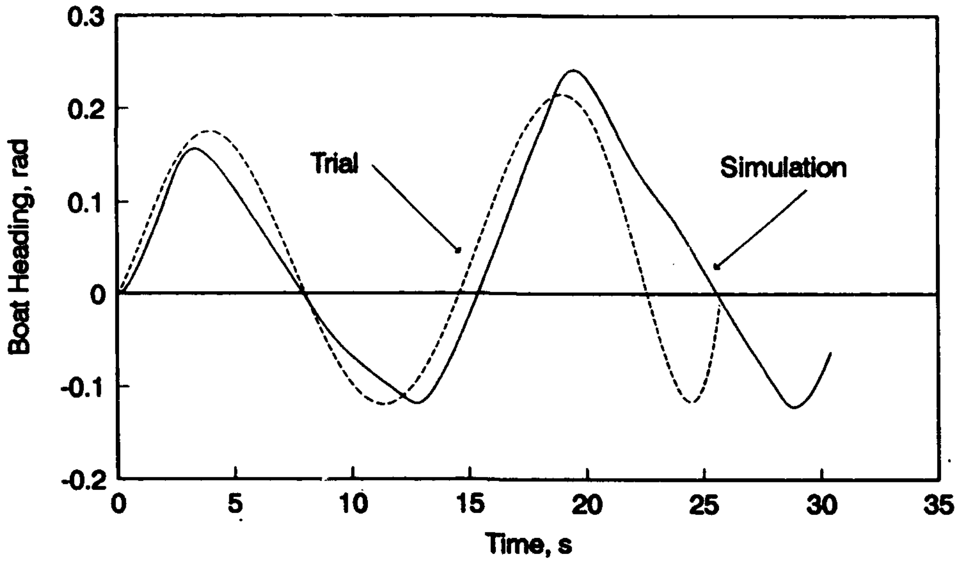

Figure 8: A 5° zigzag manoeuvre.

The model coefficients used to generate the simulated boat headings in figures (8) and (9) were:

K	=	-0.984
a	=	0.109
b	=	0.159
c	=	1.692

Figure (10) shows the comparison for a 10° zigzag manoeuvre for the drone boat with its tow load and an initial forward speed of seven knots.

The coefficients for this simulation were :

K	=	-0.555
a	=	0.110
b	=	0.141
c	=	1.120

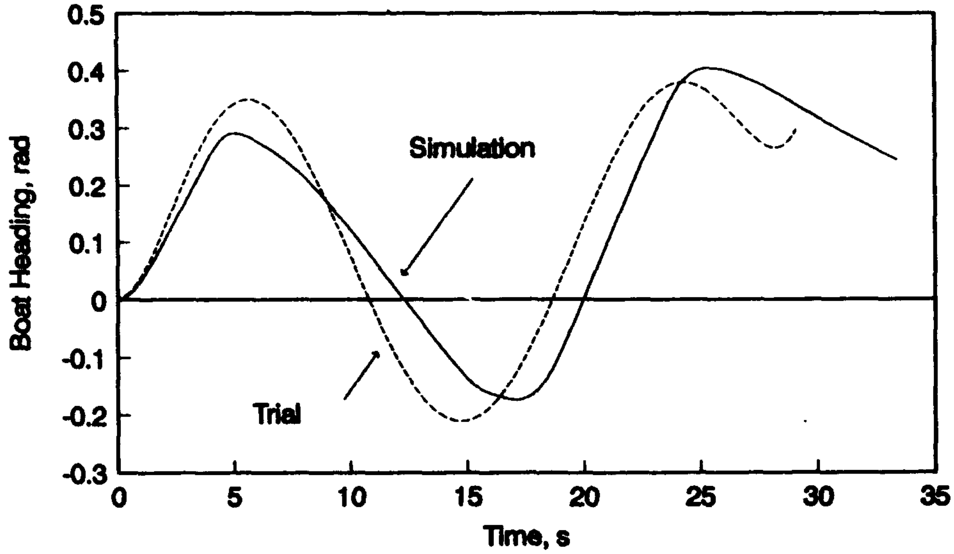

Figure 9: A 10° zigzag manoeuvre.

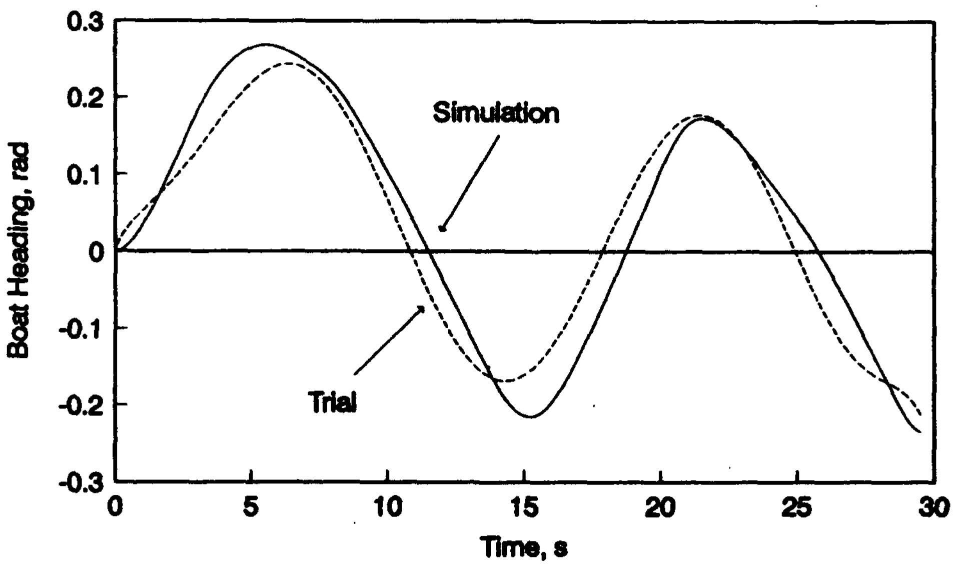

Figure 10: A 10° zigzag manoeuvre performed while towing the pipe noise maker.

6. Discussion

The literature describes various forms for mathematical manoeuvring models. The form used in this paper (equation 17) as described by Clarke(1982), was found to be the most suitable for its application to the modelling of closed loop control laws.

The zigzag is expected to be the predominant manoeuvre the drone boat will perform whilst recovering from a disturbance under the control of its autopilot. Hence the zigzag manoeuvre was deemed to be the most appropriate motion to validate the model.

Figures (8) and (9) show close agreement between simulation and trial data for two different zigzag manoeuvres with no tow load attached to the boat. The assumption that the boat and towed load can be described by the same model form appeared to be justified by the result obtained in figure (10).

At the time this work was conducted the parameters were required urgently for the subsequent simulation of autopilot proposals for the RAN and so for speed of response the model parameters were determined by trial and error. Whilst this was a somewhat tedious process, it did allow for the provision of timely advice. Trial and error appeared to be a satisfactory process for the simple model developed. However, the procedure can be automated by implementing a least squares method or by more advanced recursive methods described by Ljung(1986). This would be especially necessary for more complex models with a greater number of coefficients.

In all three comparisons it can be observed that the greatest discrepancy between simulation and actual data occurred at the points where the boat changes its direction. This error can be attributed to the fact that the model was developed from linear equations which assume that perturbations from the equilibrium state are small. Under this assumption the surge equation is neglected. Closer agreement might be obtained by including the surge equation in the model.

Notwithstanding the encouraging results obtained it should be emphasized that the model was formulated to describe a boat travelling at some forward constant speed whilst zigzagging due to small changes in the angle of thrust from a single outboard motor. This simple model was considered adequate to facilitate comparison of autopilot proposals for the drone boat.

The hull shape of the eight metre drone boat is to be geometrically similar to the six metre prototype. Therefore it is expected that the manoeuvring model developed would be applicable to the eight metre hull after dimensional scaling of the coefficients derived for the prototype boat.

7. Conclusion

This report describes a simple mathematical model of the prototype RAN precursor mine sweeping drone boat. The model was based upon the literature and describes a boat travelling along its surge axis at a constant speed produced by a constant thrust from a single outboard motor. The model predicts the yaw rate of the boat in response to small changes of the angle of thrust.

The formulation of the hydrodynamic forces acting on the boat is based on partial derivatives of the components of force with respect to the dynamic variables. The manoeuvring behaviour of the vessel is described by these derivatives.

A sea trial was held at Jervis Bay to collect manoeuvring data for the prototype drone boat. The data were used to derive coefficients for the model. These coefficients are considered to be accurate enough to provide reliable estimates of drone boat performance in still water conditions.

8. Acknowledgements

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10. *Nomenclature*

x, y, z	A set of moving, orthogonal, right hand Cartesian coordinate axes fixed to the boat, at some arbitrary origin O.
O	Arbitrary origin fixed to the boat.
x_o, y_o, z_o	A set of orthogonal, right hand Cartesian coordinate axes fixed in space to some arbitrary origin.
$\mathbf{F}$	Resultant externally applied force vector acting on the boat at the centre of gravity.
$\mathbf{M}$	Resultant externally applied moment vector acting on the boat about the origin O.
$\mathbf{M}_G$	The resultant externally applied moment vector acting on the boat about the centre of gravity.
$\mathbf{U}_G$	Linear velocity vector of the boat with respect to the centre of gravity.
$\mathbf{\Omega}_G$	Rotational velocity vector of the boat about the centre of gravity.
$\mathbf{R}$	Position vector in local coordinates of the boat centre of gravity with respect to the local origin O.
$\mathbf{\Omega}$	Rotational velocity vector of the boat about the local origin O.
$\mathbf{U}$	Linear velocity of the boat at the local origin O.
$\mathbf{I}$	Moment of inertia about the local origin O. The moment of inertia is given by a (3x3) matrix.
$\mathbf{I}_G$	Boat's moment of inertia about the centre of gravity. The moment of inertia is given by a (3x3) matrix.
t	Time.
X	Surge Force along the x-axis.
Y	Sway Force along the y-axis.
N	Moment about the z-axis.
u_o	Steady surge velocity.
u	Surge velocity.
$\dot{u}_o$	Steady surge acceleration.
$\dot{u}$	Surge acceleration.

v_o Steady sway velocity.

v Sway velocity.

$\dot{v}_o$ Steady sway acceleration.

$\dot{v}$ Sway acceleration.

r_o Steady yaw rate.

r Yaw rate.

$\dot{r}_o$ Steady yaw acceleration.

$\dot{r}$ Yaw acceleration.

ψ The instantaneous boat heading.

m Dry mass of the vehicle.

I_{zz} Moment of inertia about the z-axis.

x_G Position of the boat's centre of gravity along the x-axis.

δ Outboard motor angle.

Y_T Resolved component of thrust forces in the sway direction.

Y_H Resolved component of hydrodynamic forces in the sway direction.

Y_E Other external forces which act on the body apart from thrust and hydrodynamic forces.

N_v Damping moment derivative with respect to sway.

Y_v Damping force derivative with respect to sway.

$N_{\dot{v}}$ Added moment of inertia coefficient with respect to sway.

$Y_{\dot{v}}$ Added mass coefficient with respect to sway.

N_r Damping moment derivative with respect to yaw.

Y_r Damping force derivative with respect to yaw.

$N_{\dot{r}}$ Added moment of inertia coefficient with respect to yaw.

$Y_{\dot{r}}$ Added mass coefficient with respect to yaw.

Y_{δ} Exciting force coefficient with respect to the outboard angle.

N_{δ} Exciting moment coefficient with respect to outboard angle.

Y_{tc} Cross-track error.

A, B Points defining the position of the baseline track in (x_o, y_o) plane.

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Development of a manoeuvring model for the RAN precursor mine sweeping drone boat

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ABSTRACT

A three-degree-of-freedom mathematical model has been developed to describe the zigzag manoeuvring behaviour of a prototype hull form used in the Royal Australian Navy precursor mine sweeping drone boat. The model predicts the yaw rate of the vessel in response to the angle of thrust that a single outboard motor makes with respect to the centre line of the boat. The outboard motor is assumed to supply a constant thrust. This report describes the development of the model from first principles and its transformation into a form suitable for use in closed loop control modelling. The coefficients of the model were determined using full scale manoeuvring data for the prototype hull form.

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